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# SOME POSSIBILITIES OF DETERMINING WIND VELOCITY OVER THE OCEAN SURFACE BY SATELLITE OBSERVATIONS

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## ABSTRACT

The possibility is discussed of determining /282*
wind velocity at the near-water surface layer from the solar or lunar path observed from great altitudes.

1. The feasibility of using artificial earth satellites (AES) for meteorological investigations has brought a leading problem to the fore. This problem entails expanding the scope of available information which is essential in weather forecasting and in clarifying the optimum composition of such information. The transport of measuring equipment beyond the confines of the atmosphere precludes the possibility of using direct methods to measure the main meteorological fields - principally those of pressure, temperature, and wind velocity. Without initial knowledge of these fields, it is impossible to employ the most progressive dynamic methods of weather forecasting. Research in this area has developed chiefly in two directions.

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* Note: Numbers in the margin indicate pagination in the original foreign text.

On the one hand, the very first experiments showed that even a simple inspection of the earth from great altitudes permits positive determination of cloud field configurations, and has led to a number of discoveries substantially enriching the possibilities of nephoanalysis. Thus, the role of a theoretical base for using for meteorological purposes has, at the present state, been assigned to synoptic meteorology. This has served as a point of departure for further development in this field.

On the other hand, persistent attempts have been made to adapt the meteorological information which is accessible to AES to the requirements of numerical methods of weather forecasting. This is possible only by developing indirect methods of ascertaining pressure, temperature, wind velocity, humidity, and other meteorological fields in the troposphere from data on the radiation field leading away from the planet into space.

Certain preliminary considerations are discussed below which involve the possibility of determining wind velocity in the layer directly contiguous to a sufficiently extensive aqueous surface. This case is of particular interest, because the weather field over the oceans has still been studied very little and is not readily accessible to study by a ground observation network. We shall not touch on the obvious opportunities for directly determining wind velocity at different levels from observations of cloud movements. These methods for determining wind velocity supplement each other, as they refer to mutually-exclusive weather conditions.

2. It is well known that the agitation spectrum of a sufficiently extensive water surface is funtionally connected with wind velocity in /283

the immediately adjacent air layer. The nature of this connection is complicated by the inertial nature of the wave processes in the aqueous mass, producing clearly-expressed hysteresis phenomena. Both from the theoretical considerations and from experimental data, however, it follows that hysteresis phenomena principally manifest themselves in the long-wave section of the aqueous-surface agitation spectrum, while its quickly damped, short-wave section rather closely follows the changes in instantaneous wind velocity - in any case, if we speak of time intervals measured in minutes.

In exactly the same way, if the long-wave portion of the agitation spectrum essentially depends on the depth, size of the water basin, and shoreline contours, the effect of these factors on the short-wave section becomes negligible. Therefore, it is to be expected that a rather universal and unique connection exists between the nature of the short-wave portion of the aqueous-surface agitation spectrum and the instantaneous wind velocity in the air layer at the surface of the water.

This is corroborated, for example, by the research of Cox and Munk (Ref. 1) which was conducted in the region of the Hawaiian Islands; this research showed that the nature of the sea's surface is closely correlated with wind velocity and direction. This fact provides a basis for assuming that the average dependence of water-surface inclination distribution on wind velocity and direction - as found by Cox and Munk from measurements made in the Mid-Pacific (Ref. 1) - may also to a considerable degree be transferred to other sufficiently large water basins. We must keep the fact in mind here that the long-wave portion of the agitation spectrum makes its main contribution only to that portion of water-surface

inclination distribution which pertains to the region where its inclination is small; large surface inclination is primarily caused by the shortwave region of the spectrum.

In other words, in principle the possibility of determining wind velocity and direction in the water-level layer in an average time on the order of minutes, is afforded by distinguishing the high-frequency portion of the temporal or spatial agitation spectrum of the water surface or the inclination distribution of this surface in the area of greatest inclination.

3. Let us examine the possibilities of remote identification of the aqueous surface relief. Under natural conditions, it is reasonable to use the reflection of solar or lunar rays of light from the surface for this purpose. In the optical range of the spectrum, when the length of the light wave is incommensurably small as compared to the length of the waves running over the water surface, this surface may be regarded as a set of differently-oriented areas, i.e., diffraction phenomena may be disregarded (which is not now possible in the radio range), if, of course, we limit ourselves to cases where there is no foam, which occurs in open basins in perceptible quantities only with a very strong wind (this case must be separately examined).

The reflection of light from every element of the surface will then follow Fresnel's law, only in the direction dictated by Snell's law. In the proper direction, the brightness of the direct sunlight or moonlight reflected by the surface element will be far greater than the brightness of the light diffused in the depths of the waters and emanating in the

same direction through the same element of the water surface. With other orientations of the water-surface element in the same direction, the direct light of the celestial body will no longer be reflected, but its light will be diffused by the atmosphere, i.e., it will have considerably less brightness.

Let us now assume that we are continuously observing a water-surface element from a given direction. Against a fluctuating background of comparatively small brightness (caused by the reflection of the celestial vault and the diffused light issuing from the watery depths), we shall observe bright flashes occurring when the surface element is oriented to the celestial body in conformity to Snell's law. It is obvious that the time spectrum of these flashes is determined by the agitation spectrum and may be used to determine this spectrum. In just the same way, the instantaneous spatial distribution of the flashes (more precisely, the spatial spectrum of this distribution) will reflect the water-surface agitation spectrum. In order to carry out both these methods, however, it is necessary to have high angular resolution, which is possible only at small distances between observer and water surface. /284

Let us now imagine that the linear dimensions of the visual field of the measuring instrument are substantially greater than the wave-length scale on the water's surface. The employment of such an instrument will correspond to spatial (temporal) averaging of the brightness of the light reflected by the water surface, and its readings will be determined by the form of the time-averaged distribution function of the water-surface elements with respect to orientation. Determination of this function may

therefore be reduced to measuring the angular distribution of the brightness of the light reflected by the sea's surface, appropriately averaged in space or time. This must take into consideration, of course, the Fresnel dependence of the reflection coefficient on the angle of incidence, and corrections must be introduced for reflection of the celestial vault by the water surface and for brightness of the light emanating from the depths of the waters.

The brightness of a celestial body is always far greater than that of its light diffused in water or air. The distribution of the surface elements with respect to orientation is close to Gaussian distribution, and has a comparatively small half-width (Ref. 1). Therefore, the direct light of the sun or moon reflected by the water surface is principally concentrated in a comparatively small angular region and forms the so-called path of the sun or moon. Within the confines of this path, the brightness of the surface-reflected direct light of the celestial body is much greater than the brightness of its scattered light which is reflected or which penetrates the surface, and it is possible to neglect the latter. This is particularly important, for, if it were necessary to take the effect of the scattered light into consideration, additioanl data on the state of the atmosphere at a given moment in time would be required and would make it impossible to accomplish the task of determining the form of the water surface.

Furthermore, the effect of the distribution function, with respect to orientation, of the water-surface elements on the parameters of the light path is far greater than on the brightness of the water surface

beyond the limits of the path (because of the diffuseness of the angular distribution of the scattered light).

Finally, since, in the last analysis, we are interested not in the water-surface form itself, but only in wind velocity and direction, the measurement problem is essentially narrowed and is reduced to determining those parameters of the sun or moon path which depend directly on the wind to the greatest degree.

On the basis of the above statements, we may formulate the investigation problem as follows. In principle, if the water's surface is illuminated by direct rays of the sun or moon, and clouds do not shield it from the observer (which, as is known, occurs on the average of about 50% of the time), it is then possible to determine wind velocity and direction by measuring the brightness characteristics of the sun or moon path on the surface of the water. The following is necessary in order to employ this method:

(a) We must know the effect of the wind and position of the celestial body on the characteristics of the light path, as well as the /285 degree of stability of this effect and the nature of its variations;

(b) We must determine the path parameters most sensitive to wind changes and the most favorable conditions for finding them;

(c) We must ascertain the sensitivity of the method and the possible errors entailed in determining wind velocity and direction.

4. The effect of water-surface relief or wind velocity on light-path characteristics has been investigated in a number of papers (Ref. 1-6). Both the scope and the nature of the data derived in them is insufficient

to answer the questions raised. Cox and Munk's already-mentioned work (Ref. 1) - in which the authors experimentally derived a specific type of distribution function of surface elements with respect to orientation and also the function's dependence on wind velocity and direction - is of the greatest interest with respect to the foregoing. Their data show that the stability of wind direction exerts a certain influence on the form of the distribution function by increasing its extension in the wind direction, while wind force variability entails restriction of its half-width. However, the wind stability effect is not great. Correlation factors with wind velocity determined experimentally show that the average error of determining wind velocity from the known distribution function of inclination with respect to orientation is about $\pm$ 1 m/sec. The experimental findings of other authors (Ref. 3-6) are found to be in good qualitative agreement with the data of Cox and Munk.

The effect of the form of the distribution function for water-surface inclination on the light-path parameters is examined in Ref. 7-9. These works present the principal results obtained by one of the authors from detailed calculations of the brightness and polarization of the light path on an agitated aqueous surface, as a function of position of celestial body and wind velocity. The distribution function of surface elements with respect to orientation, borrowed from Ref. 1, was made on the basis of that computation.

The general nature of the dependence of the light-path isophots (solid lines) and isopolars (broken lines) on zenith distance of the

sun, and wind velocity and direction is given in Figures 1-3.

The data obtained make it possible to solve the problem of selecting path parameters most sensitive to wind and to evaluate the accuracy with which it is possible to determine the latter.

One of the most characteristic features of the light-path is the shift in maximum brightness relative to the angle of mirror reflection. This shift increases rapidly as wind velocity $\nu$ becomes greater, as Figure 2 clearly indicates. Figure 4 depicts the dependence of the magnitude of this shift $\Delta z$ on $\nu$ for differing zenith distances $z$ of the celestial body (the horizontal parts of the curves correspond to position of maximum brightness on the horizon). As is evident, with average $z$ values (25 - 60°) the magnitude of $\Delta z$ is extremely sensitive to changes in $\nu$. In particular, when $z \approx 40°$ the magnitude of $d(\Delta z)/d\nu$ is about 2° per 1 m/sec when $\nu < 5$ m/sec and about 10° per 1 m/sec when $\nu = 7 - 10$ m/sec, which makes comparatively small demands on accuracy in measuring the position of maximum brightness. It must be borne in mind, however, that with sufficiently large values of $\nu$ or $z$, maximum brightness is displaced into the horizon region and becomes inaccessible to measurement because of the masking effect of atmosphere haze.

Therefore, the dependence of $\Delta z$ on $\nu$ may be utilized to determine $\nu$ only in the restricted intervals of $z$ which are displaced as a function of $\nu$.

As follows from Figure 3, the inclination of wind direction to the solar meridian causes displacement of maximum brightness with respect to this meridian. Analysis shows that this displacement also increases with /286

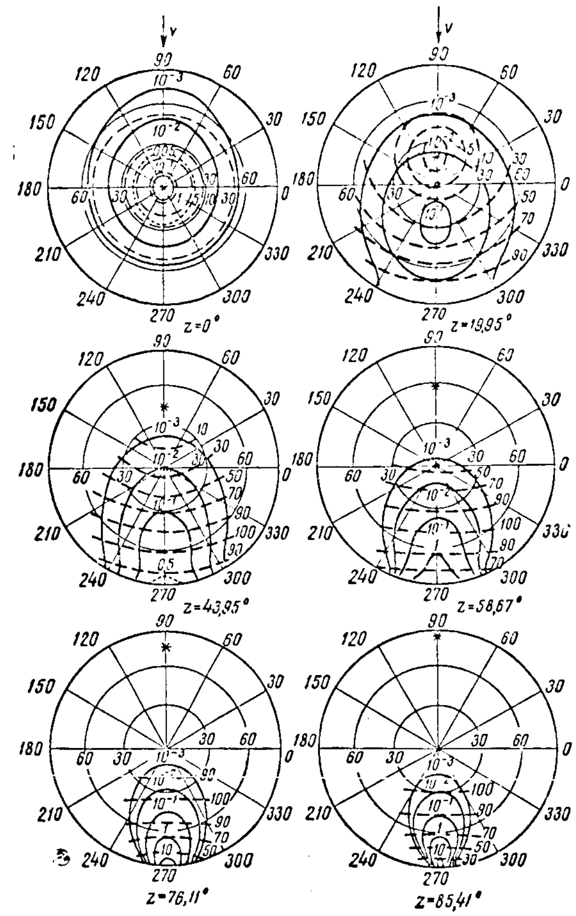


Figure 1

Isophots and Isopolars of Light Path on an Agitated Sea Surface with Differing Solar Zenith Angles z (wind velocity $\nu$ = 10 m/sec; wind direction from the sun)

wind velocity and depends on wind direction, but even when $\nu$ = 15 m/sec, it does not exceed several degrees, and we may rely on being able to find wind direction from this characteristic only with large values of $\nu$. But the general configuration of the isophots is sufficiently sensitive to wind direction and may be used to determine it.

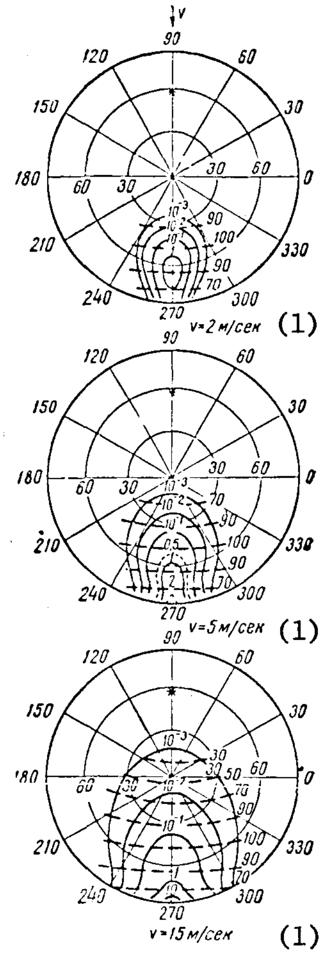


Figure 2

Isophots and Isopolars of Light Path on an Agitated Sea Surface with Differing Wind Velocities ν (zenith distance of sun z = 58.67°; wind direction from the sun)

(1)- sec

We should note that, although the position of the isopolars does not depend on wind velocity, the degree of polarization at maximum brightness noticeably depends on ν. Moreover, the light of the haze separating the observer from the water surface is also polarized, and since the interference from haze is hard to foresee, the degree of polarization can

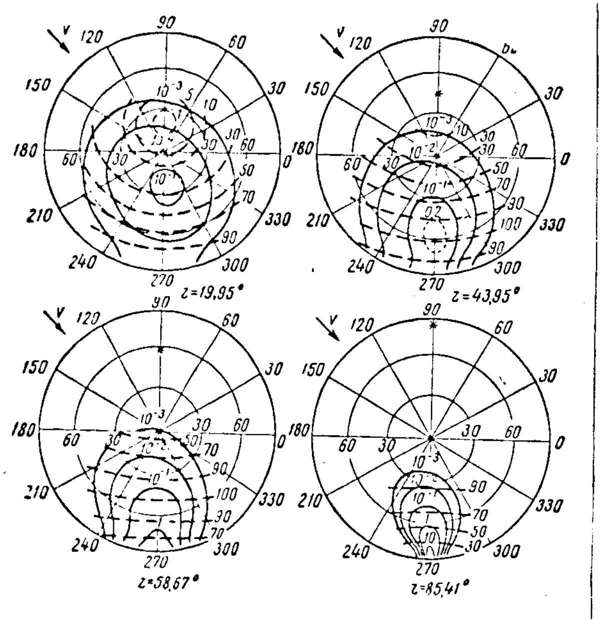


Figure 3

Isophots and Isopolars of Light-path on the Agitated Sea Surface with Different Solar Zenith Distance z and Wind Direction at a 45° Angle to the Solar Meridian -- see arrows (wind velocity $\nu$ = 10 m/sec)

scarcely serve to determine $\nu$.

Another light-path parameter which is highly dependent on wind velocity is width. We choose the value $\alpha$, defined as the angular distance between two points on a perpendicular to the solar meridian and corresponding to /287
the same brightness $I = 0.1I_0$, as the criterion of width. [$I_0$ is the brightness at a point corresponding to the mirror reflection from which the perpendicular is drawn (Figure 1).] Figure 5 displays the dependence of $\alpha$ on z at different values of $\nu$. For values of z which

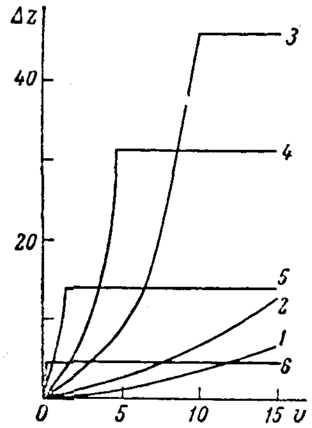


Figure 4

Dependence of Displacement $\Delta z$ of Light-Path Brightness Maximum with Respect to Mirror-Reflection Angle on Wind Velocity $\nu$ (Wind Direction From the Sun) For Different Solar Zenith Distances z: 1 — $z = 0°$, 2 — $z = 19.95°$, 3 — $z = 43.95°$, 4 — $z = 58.67°$, 5 — $z = 76.11°$, 6 — $z = 85.41°$

are not too large, the ratio $d\alpha/d\nu$ exceeds $3°$ per 1 m/sec, which does not make too rigid demands on measurements of $\alpha$. However, it does demand rather accurate measurements of I, which are in substantial measure hindered by atmospheric haze.

The absolute value of light-path brightness, particularly at its maximum (Figure 6), also depends greatly on wind velocity. However, the utilization of this dependence requires absolute measurements of brightness - which is in itself a more complex task - as well as consideration of the effect of atmospheric haze, and this can hardly be done with the proper degree of accuracy. Therefore, this method cannot be recommended - in any case, not without further investigation. It is even more impossible to recommend the utilization of light-path brightness when its maximum is

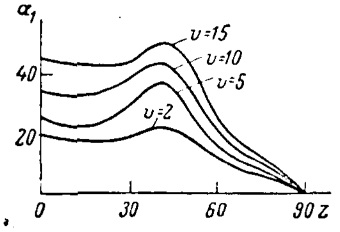


Figure 5

Dependence of Angular Width $\alpha$ of Light Path on Solar Zenith Distance at Different Wind Velocities

displaced toward the horizon.

If we turn our attention to the rapid decline in path brightness while its width quickly broadens with an increase in $\nu$, it becomes apparent that the most characteristic parameter is the transverse brightness gradient, e.g., at a given angular distance $\phi$ from the solar meridian along a perpendicular erected at the mirror reflection point. Figure 7 displays the dependence on $\nu$ of this gradient $dI/d\phi$ when $\phi = 260°$ (see Figure 1) for different solar zenith distances. Besides the sensitivity of this parameter to $\nu$, one advantage of this parameter is that: /288

(a) It may be directly measured and with increased accuracy corresponding to the differential arrangement;

(b) It can be measured on both sides of the solar meridian, which permits the introduction of corrections for wind direction; and

(c) Atmospheric haze effect is practically excluded because of its slight dependence on $\phi$ at the observational angles which are of practical interest.

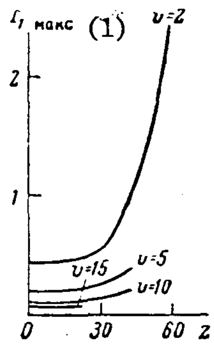


Figure 6

Dependence of Maximum Light-Path Brightness on Solar Zenith Distance with Differing Wind Velocities

(1)- max

Use of this parameter, however, requires the completion of absolute brightness measurements. This may be avoided if, instead of $dI/d\phi$, the ratio $d \lg I/d\phi$ is measured - i.e., the logarithmic brightness gradient - but its sensitivity will be poorer and the haze effect more severe. This method, moreover, requires sufficiently precise orientation with respect to the solar meridian. We would like to note in this connection that measurements of polarization plane direction make it possible to determine the direction of the solar meridian with an accuracy on the order of 3-4° (Ref. 8). This is sufficient to determine $\nu$ from the light-path characteristics.

Finally, as already noted, in principle it is possible to determine the brightness isophot configuration (in particular, from photographs by equidensitometric methods, for example). This should enable us to make a much more detailed and reliable analysis from the standpoint of ascertaining wind velocity and direction, but it entails significant substantial complications in performing the experiment. It may be a compromise to

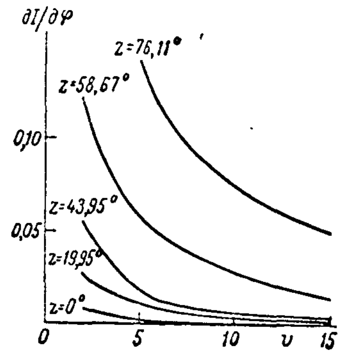


Figure 7

Dependence of Velocity Gradient dI/d$\phi$ in Vicinity of Direction of Mirror Reflection for $\phi$ = 260° at Different Solar Zenith Distances

measure light-path brightness simultaneously in several different directions, the selection of which, however, requires special investigation.

5. The analysis did not take into account the celestial light reflected from an aqueous surface or the scattered light emanating from watery depths. It has already been remarked above that their brightness in the light-path region is small and need not be considered. On the edges of the light path, however, it becomes substantial, and may prove /289 to be the source of serious errors when finding the value of $\alpha$. Even greater errors in determining this value may result from the luminous veil caused by the scattering of light in the column of air separating the observer from the aqueous surface. Therefore, in practice we shall scarcely be able to use this value to find $\nu$.

Atmospheric haze, as already mentioned, must introduce essential errors into measurements of light-path brightness and polarization, and practically makes it impossible to measure them in the vicinity of the

horizon. Atmospheric haze, however, will affect the position of maximum brightness comparatively slightly, and will have practically no effect on its transverse gradient. Therefore, it is precisely these parameters which should be recommended for determining $\nu$ from high-altitude observations of the water surface.

It is advisable to use the red region of the spectrum for measurements because the effects of scattering, both in air and water, are perceptibly weaker in this region. On the other hand, it is recommended that polarizing optics be employed, because - as a result of the considerable difference in degree of polarization of the surface-reflected light and light scattered by the atmosphere - the effect of atmospheric haze and of light scattered in the watery depths may be cut almost in half.

Preliminary calculations show that within the limits of reasonable variations in atmospheric turbidity, in the red sector of the spectrum when an analyzer is used - for zenith distances of a heavenly body which are not too large and for the sighting direction - the light-path brightness is in any case several times greater than the brightness of the diffused-light background, which completely ensures the requisite accuracy in determining the position of maximum brightness or the degree of its transverse gradient.

6. It follows from this analysis that under comparatively frequently-occurring conditions, observations of the light path on a sufficiently-extensive water surface, which are made from great altitudes (particularly from AES), make it possible to find the water-level layer wind velocity

averaged over short intervals of time. From this viewpoint, the best path parameters are the position of maximum brightness and its transverse gradient. Estimates demonstrate that at moderate zenith distances of sighting direction and sun, for a relative brightness-measuring error on the order of 2-3%, and for an angle-detection error of 2-3°, it is possible to ascertain wind velocity with an error of about $\pm$ 2 m/sec. As for the wind direction, without detailed tracing of the isophot shapes, we can rely only on coarse estimates and then only for large $\nu$ values.

Further development of the described method requires a detailed investigation of the distribution function of elements of the agitated aqueous surface with respect to orientation, as well as of its dependence on wind velocity and of the hysteresis effects belonging to it. Such an investigation is essential for the problem of weather forecasting from another point of view. As computations have shown, the albedo and radiative capacity (near the horizon) of a water surface, which exert a great effect on the thermal properties of waters and their radiant heat exchange with the atmosphere, depend on the nature of this function in great degree.

In conclusion, let us once more point out that the above-considered problem represents a particular case of the more general problem of extracting meteorological data from the angular structure of the radiation field departing from the planet into space, and by no means exhausts the potentialities which here exist.

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